Lecture Notes

for

Operational Amplifier

(PHYS4008: Electronics)

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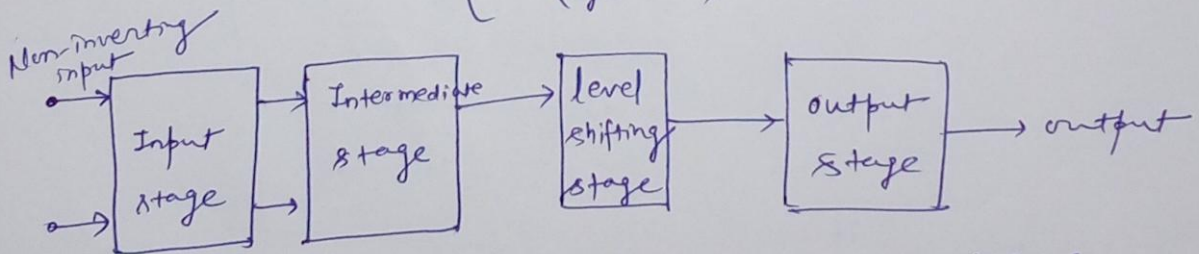
Operational Amplifiers (op-amp)

An operational amplifier is a direct coupled high gain amplifier usually consisting of one or more differential amplifiers & usually followed by a level translator & an output stage of push-pull or push-pull complementary symmetry pair.

* It is available as a single Integrated circuit package.
* It is a versatile device used to amplify dc as well as ac input signals.
* It was originally designed for performing mathematical operations such as addition, subtraction, multiplication, differentiation & integration.
* Applications:
  - ac & dc signal amplification
  - active filters
  - Oscillators
  - Comparators
  - Regulators

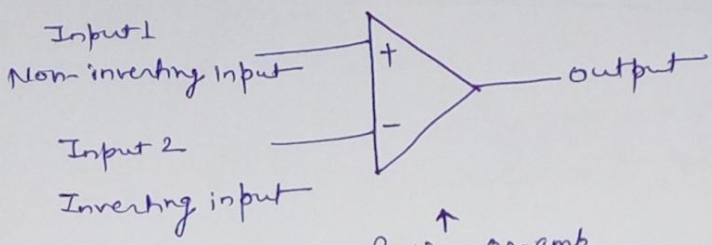


inverting input → Dual-input balanced output Differential Amplifiers

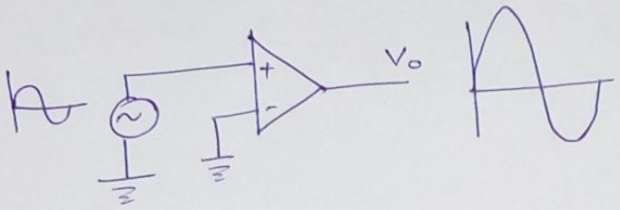
emitter follower using constant current source

Complementary symmetric push-pull amplifier

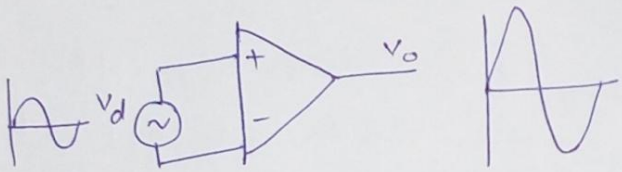
Dual input unbalanced output DA



Basic Op-amp

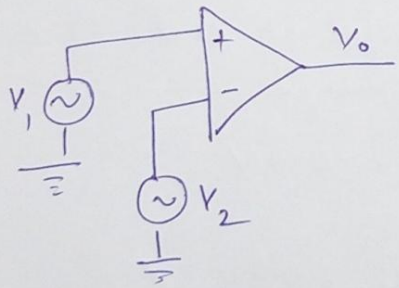


⇐ Single-ended operations

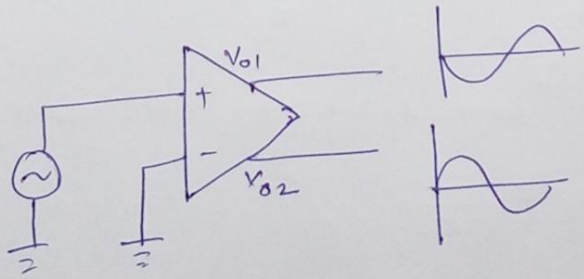


⇐ Double-ended (differential) operation

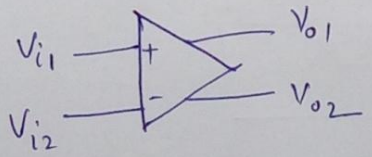
or



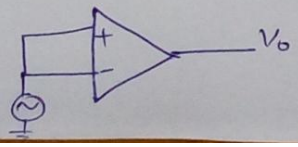
⇐ " "



⇐ Double-ended output with single-ended input

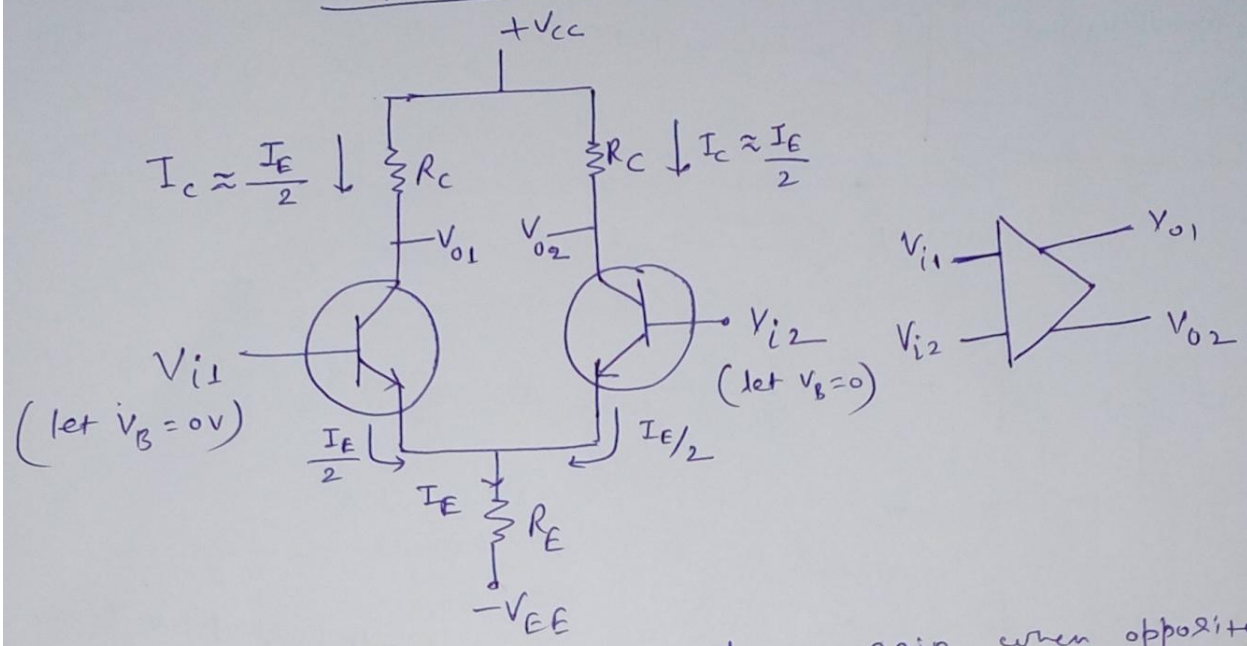


Double ended input & outputs.



Common-mode operation

Differential Amplifier circuit.



* The main feature is very large gain when opposite signals are applied to the inputs as compared to very small gain resulting from common inputs.

DC Bias

with each base voltage at 0 V. The common-emitter dc bias voltage is

$$V_E = 0 - V_{BE} = -0.7\,V$$

$$I_E = \frac{V_E - (-V_{BE})}{R_E} \approx \frac{V_{EE} - 0.7\,V}{R_E}$$

Assuming that both transistors are well matched

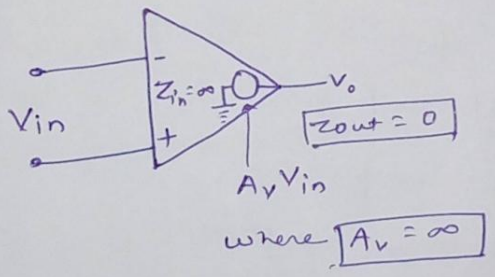
$$I_{e_1} = I_{e_2} = \frac{I_E}{2}$$

& $V_{C_1} = V_{C_2} = V_{CC} - I_C R_C$

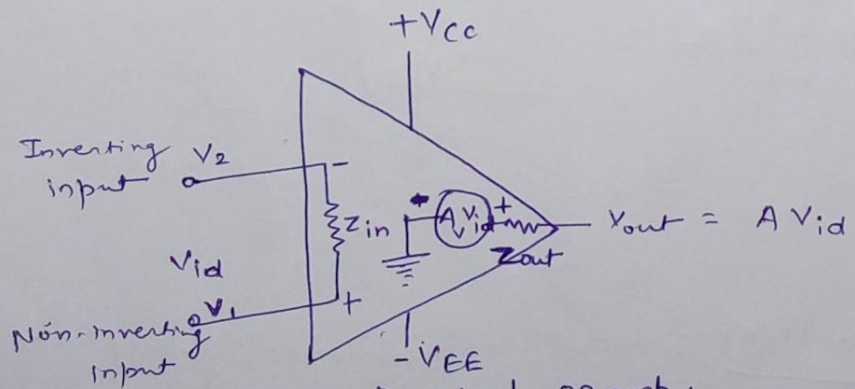
$$\boxed{V_{C_1} = V_{C_2} = V_{CC} - \frac{I_E}{2} R_C}$$

Ideal OP-AMP

1. Infinite voltage gain A.
2. Infinite input resistance R_i so that almost any signal source can drive it and there is no loading of the preceding stage.
3. Zero output resistance R_o so that it can drive an infinite no. of other devices.
4. Zero output voltage when input voltage is zero.
5. Infinite bandwidth (any signal (0 to ∞ Hz) can be amplified without attenuation.
6. Infinite common-mode rejection ratio so that the output common-mode noise voltage is zero.
7. Infinite slew rate so that the output voltage changes occur simultaneously with input voltage changes.

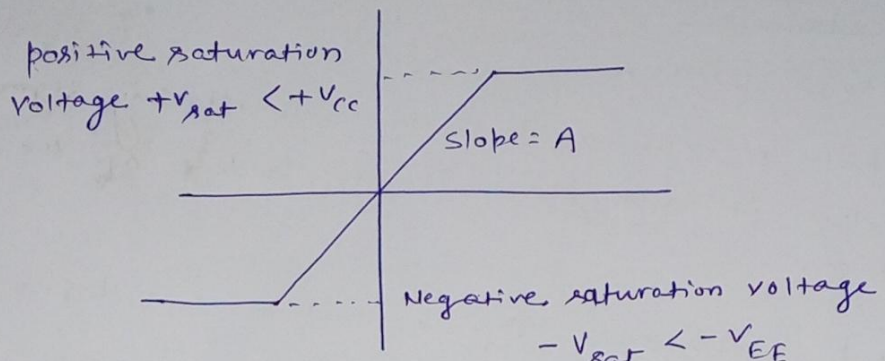


Ideal OP-Amp



Practical OP-amp.

* Slew rate (SR) = $\frac{\Delta V_o}{\Delta t}$ V/μs



Ideal voltage transfer curve.

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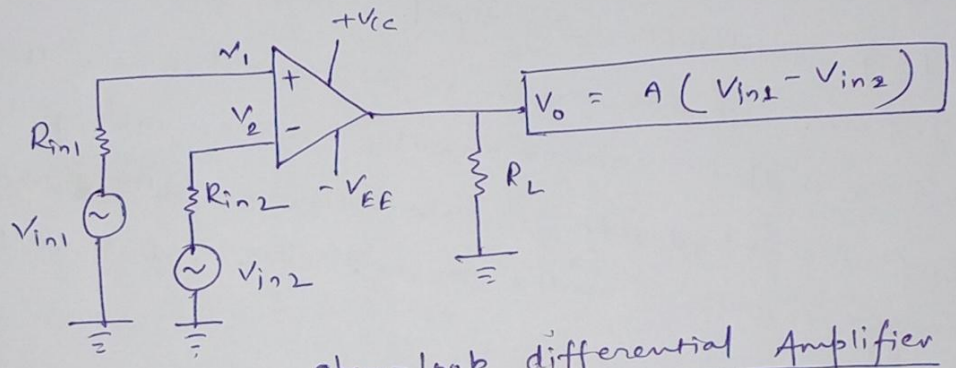
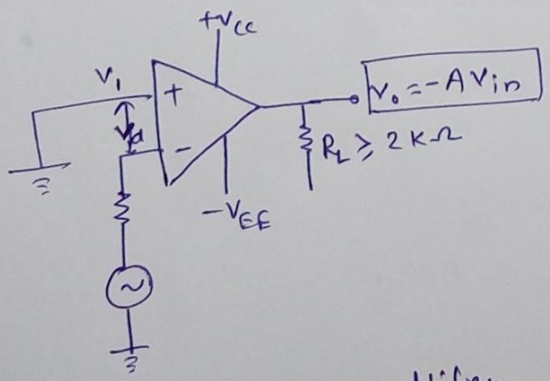


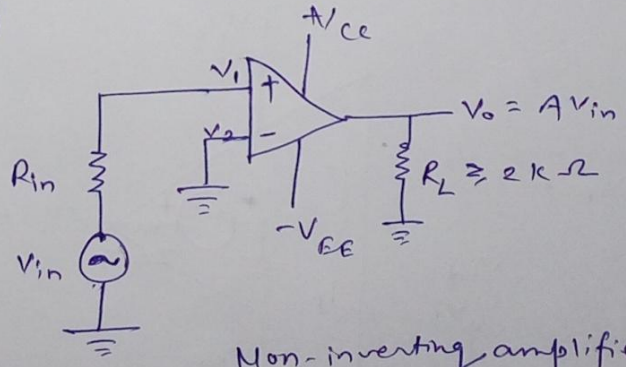
Open-loop differential Amplifier

* There are three open-loop op-amp configurations.

1. Differential amplifier
2. Inverting amplifier
3. Non-inverting amplifier



Inverting amplifier



Non-inverting amplifier.

* Input Offset Voltage: The voltage that must be applie between the two input terminals of an op-amp to null the output.

* Input offset current: The algebraic difference between the currents into inverting and non-inverting terminals is referred to as input offset current.

* Input Bias current: The average of the currents that flows into the inverting and non-inverting input terminals of the op-amp.

$$I_B = \frac{I_{B1} + I_{B2}}{2}$$

* Differential Input Resistance: The equivalent resistance that can be measured at either inverting or non-invertin input terminals with other terminal connected to ground.

* Input Capacitance: The equivalent capacitance that can be measured at either inverting or non-inverting terminal with other terminal connected to ground.

* Common-Mode Rejection ratio: (CMRR)

$$\boxed{CMRR = \frac{A_d}{A_{cm}}} \quad \& \quad \boxed{CMRR(log) = 20 \log_{10} \frac{A_d}{A_{cm}}}$$

* Output Voltage Swing: The output voltage never exceeds the limit of given supply voltages, $+V_{CC}$ & $-V_{EE}$.

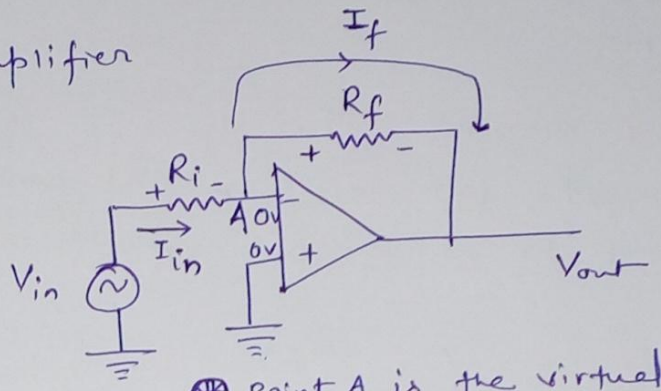
* Output Resistance: The equivalent resistance that can be measured betn the output terminals of op-am and ground. eg: 75Ω for the 741C op-amp.

* Supply current: The current drawn by the op-amp from the power supply.

for 741C: $I_S = 2.8\,mA$

Applications of Op-Amps

1. Inverting Amplifier



Point A is the virtual ground.

$$I_{in} = \frac{V_{in} - V_A}{R_i} = \frac{V_{in} - 0}{R_i} = \frac{V_{in}}{R_i}$$

$$I_f = \frac{V_A - V_{out}}{R_f} = \frac{0 - V_{out}}{R_f} = \frac{-V_{out}}{R_f}$$

Since $I_f = I_{in}$ (for ideal op-amp)

$$\frac{-V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

Voltage gain $\boxed{A_{CL} = \frac{V_{out}}{V_{in}} = \frac{-R_f}{R_i}}$

* The closed-loop voltage gain is independent of the op-amp's internal open-loop voltage gain.

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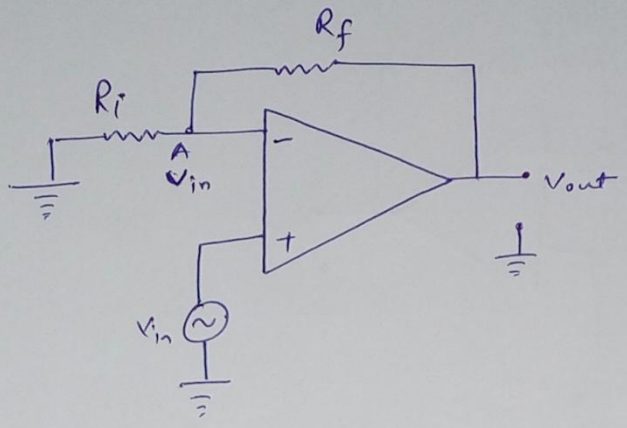
2. Non inverting Amplifier



Current through R_i = Current through R_f

$$\frac{V_{in} - 0}{R_i} = \frac{V_{out} - V_{in}}{R_f}$$

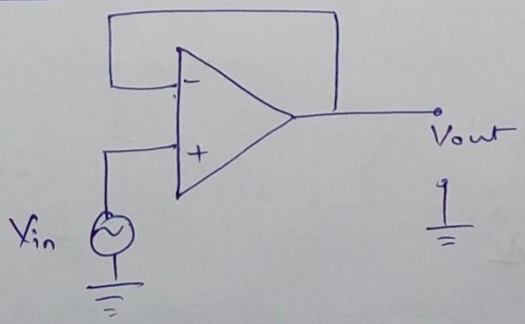
$$V_{in} R_f = V_{out} R_i - V_{in} R_i$$

$$V_{in} (R_f + R_i) = V_{out} R_i$$

$$\frac{V_{out}}{V_{in}} = \frac{R_f + R_i}{R_i} = 1 + \frac{R_f}{R_i}$$

$$\boxed{A_{CL} = 1 + \frac{R_f}{R_i}}$$

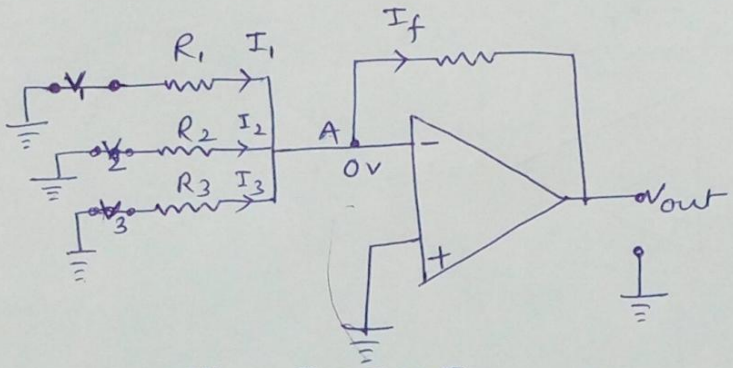
3. Voltage follower



$$A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{0}{R_i} = 1$$

* It have very high input impedance & very low output impedance. Hence, it is nearly ideal buffer amplifier to be connected betn high impedance source & low z load

4. Summing Amplifiers



$$I_f = I_1 + I_2 + I_3$$

$$V_{out} = -I_f R_f$$

$$= -R_f (I_1 + I_2 + I_3)$$

$$\boxed{V_{out} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)}$$

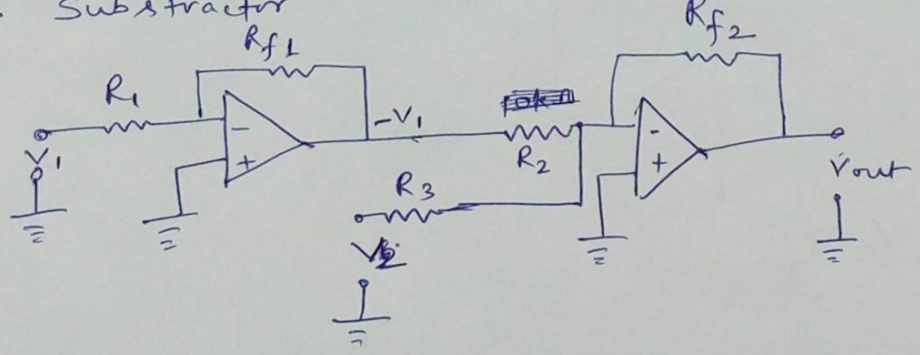
If $R_1 = R_2 = R_3 = R$, we have

$$\boxed{V_{out} = -\frac{R_f}{R} (V_1 + V_2 + V_3)}$$

again, if gain is unity

$$\boxed{V_{out} = -(V_1 + V_2 + V_3)}$$

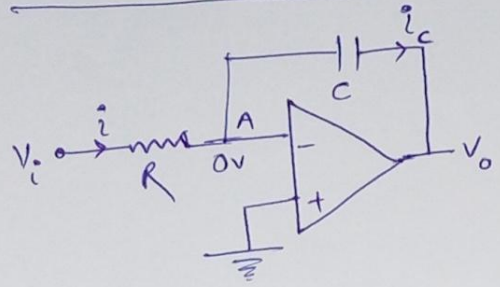
5. Substractor



$$\boxed{V_{out} = V_1 - V_2}$$

(if both op-amp have $R_3 = R_1 = R_{f1} = R_{f2} = R_2$

6. OP-Amp Integrator



Since $i = i_c$ for ideal op-amp.

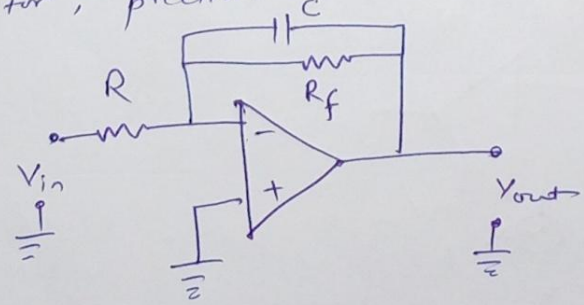
$$\frac{V_i}{R} = \frac{C dV_c}{dt} \qquad (\because \text{Voltage across capacitor } V_c = 0 - V_o = -V_o)$$

$$\frac{V_i}{R} = -C\frac{dV_o}{dt}$$

$$\frac{dV_o}{dt} = -\frac{1}{RC} V_i$$

$$\therefore \boxed{V_o = -\frac{1}{RC}\int_0^t V_i\, dt}$$

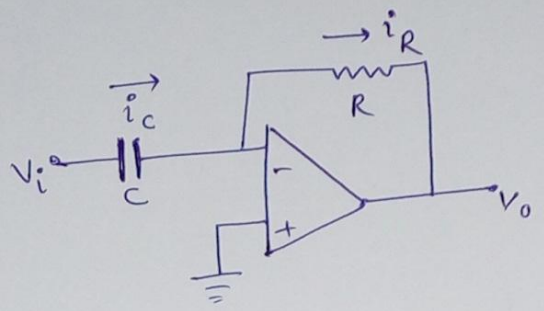
* It has serious disadvantage in low frequency applications. By connecting a feedback resistor R_f in parallel with capacitor, precise closed-loop voltage gain is possible.



$$\boxed{f_c = \frac{1}{2\pi R_f C}}$$

f_c is the critical frequency below which the above circuit cannot perform proper integration. It will behave as inverting amplifier.

7. OP-Amp differentiator



$$i_C = i_R$$

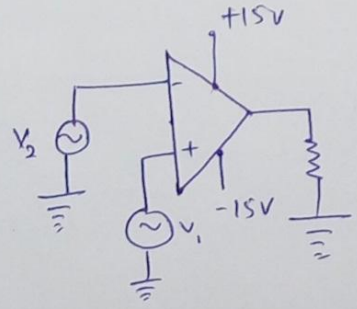
$$C\frac{dV_C}{dt} = \frac{-V_0}{R}$$

$$C\frac{dV_i}{dt} = \frac{-V_0}{R} \qquad (\because V_C = V_i - 0 = V_i)$$

$$\boxed{V_0 = -RC\frac{dV_i}{dt}}$$

8. Comparators

A comparator is an op-amp circuit without negative feedback and takes advantage of very high open voltage gain of op-amp.

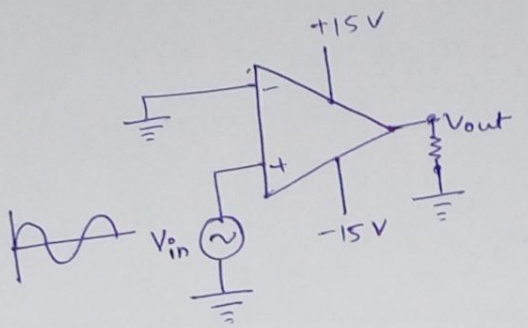


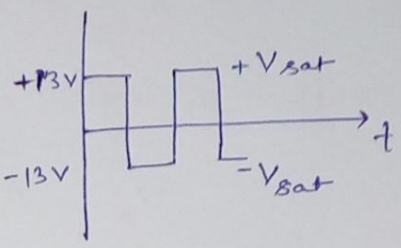
If differential input is +ve, the circuit is driven to saturation and output goes to max^m +ve value.

* It uses no feedback so that the voltage gain is equal to the open-loop voltage gain of op-amp.

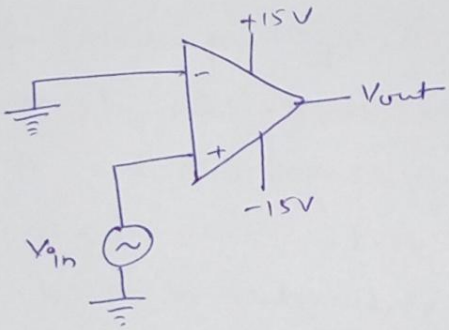
* It is operated in a non-linear mode.

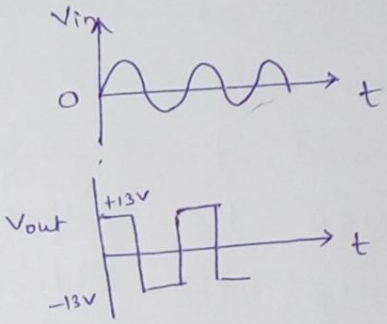
1. As a square wave generator.



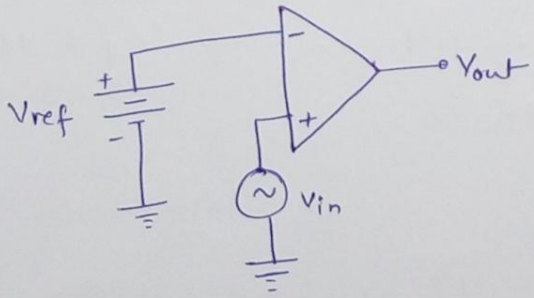


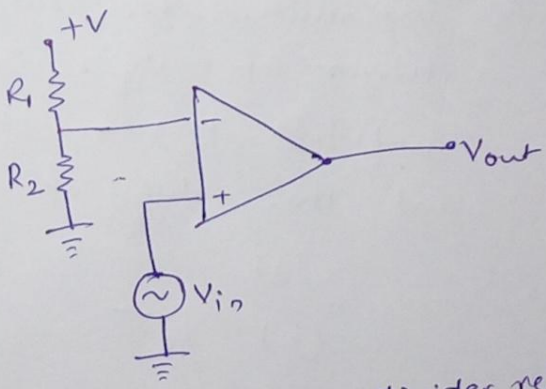
2. As a zero-crossing detector





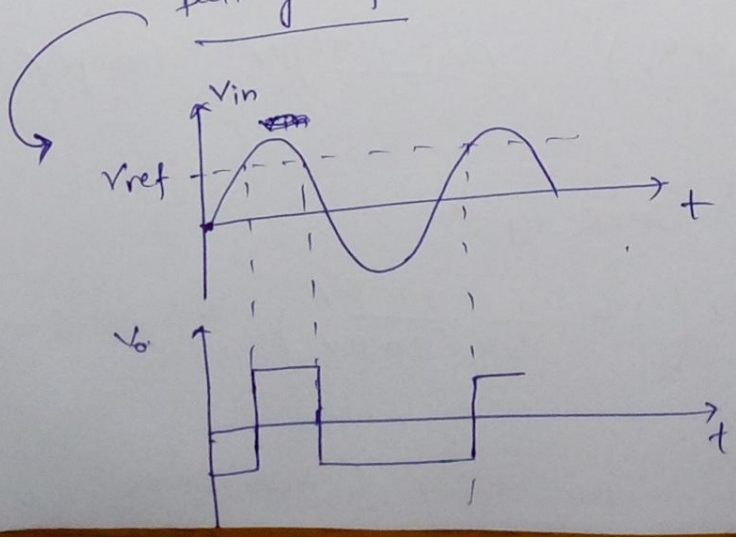
3. As a level detector





Battery ref.

Voltage divider ref



Common inputs in Op-amp

$$V_c = \frac{1}{2}(V_{i1} + V_{i2}) \longrightarrow (i)$$

output voltage

$$V_o = A_d V_d + A_c V_c \longrightarrow (ii)$$

$$V_o = A_d V_d \left(1 + \frac{A_c V_c}{A_d V_d}\right) \Rightarrow \boxed{V_o = A_d V_d \left(1 + \frac{1}{CMRR}\frac{V_c}{V_d}\right)}$$

Even when both V_c & V_d components of signals are present, the eqn shows that for large value of CMRR, the output voltage will be due to mostly differential signal & common-mode component greatly reduced or rejected.

Q Determine the output voltages of op-amp for input voltages of $V_{i1} = 150\,\mu V$ and $V_{i2} = 140\,\mu V$. The amplifier has a differential gain of $A_d = 4000$ and the value of CMRR is

(a) 100

(b) 10^5

Soln $V_d = V_{i1} - V_{i2} = (150 - 140)\,\mu V = 10\,\mu V$

$$V_c = \frac{1}{2}(V_{i1} + V_{i2}) = \left(\frac{150 + 140}{2}\right)\mu V = 145\,\mu V$$

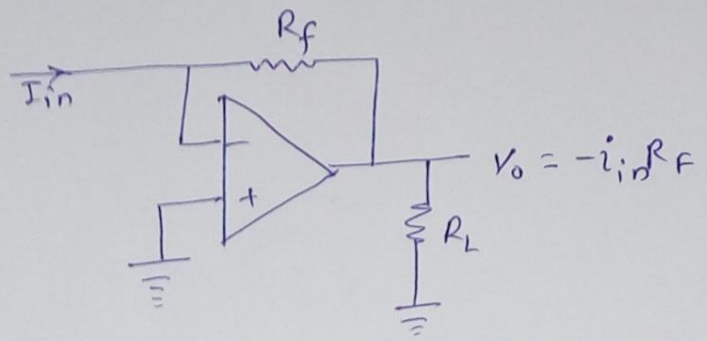
$$V_o = A_d V_d \left(1 + \frac{1}{CMRR}\frac{V_c}{V_d}\right)$$

(a) $V_o = 4000 \times 10\,\mu V \left(1 + \frac{1}{100}\frac{145\,\mu V}{10\,\mu V}\right) = 95.8\,mV$

(b) $V_o = 40.006\,mV$.

* This Question shows the effect of high CMRR.

Current to Voltage converter



$$\frac{V_o}{V_{in}} = -\frac{R_f}{R_{in}} \quad \text{(for inverting amplifier)}$$

$$V_o = -\frac{R_f}{R_{in}} V_{in} = -\left(\frac{V_{in}}{R_{in}}\right) R_f$$

$$\frac{V_{in}}{R_{in}} = i_{in}$$

hence, $\boxed{V_o = -i_{in} R_f}$

It indicates that the V_{in} & R_{in} Combination is replaced by current source i_{in}. The output voltage V_o becomes proportional to the input current I_{in}. Hence, the above circuit converts the input current into a proportional output voltage.

* It is used in sensing the current from photodetectors and digital to Analog converter applications.

open loop gain	(∞)	very high $\geq 10^4$
open loop Bandwidth	(∞)	very high
Common mode rejection ratio	(∞)	High $(\geq 70dB)$
Input resistance	(∞)	High $(\geq 10M\Omega)$
Output resistance	(0)	low $(< 500\Omega)$
off-set voltage and current	(0)	low $(< 10mV; < 0.2nA)$

* Slew rate

$$S_R = 2\pi f_{max} V_p$$

V_p = peak of the output sin wave.

f_{max} = highest undistorted frequency

References:

1. Op-Amps and Linear Integrated Circuits by R. A. Gayakwad
2. Linear Integrated Circuits by D. R. Choudhury and S. B. Jain
3. Electronics Fundamentals and Applications by D. Chattopadhyay and P.C. Rakshit
4. Electronic Devices and Circuits by J. Millman and C.C. Halkias
5. Integrated Electronics by J. Millman and C.C. Halkias